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Calibration and Validation of Measurement System

Wave Dragon, Nissum Bredning

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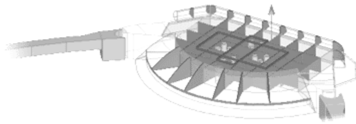

Calibration and Validation of Measurement System – Wave Dragon, Nissum Bredning


Project:

Sea Testing and Optimization of Power Production on a Scale 1:4.5 Test Rig of the Offshore Wave Energy Converter Wave Dragon

according to EU ENERGIE contract no. ENK5-CT-2002-00603

Jens Peter Kofoed, Aalborg University
Sven Riemann & Wilfried Knapp, Technical University Munich

March, 2004

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Hydraulics and Coastal Engineering No. 2

Calibration and Validation of Measurement System

Wave Dragon, Nissum Bredning

by

Jens Peter Kofoed, Aalborg University
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March, 2004

Table of contents

1. Introduction

This report deals with the calibration of the measuring equipment on board the Wave Dragon, Nissum Bredning (WD-NB) prototype.

The report covers the following instruments on board WD-NB:

- Pressure transducers.
- Force transducers.
- Accelerometers.
- Displacement sensors.
- Strain gauges.
- Inclinometers.

All of these instruments are connected to the HBM MGC+ amplifier and data acquisition unit. In the following the calibration will be dealt with individually.

Furthermore, a preliminary calibration of the siphon and dummy turbines has been carried out and this is also described in the following.

2. List of transducers

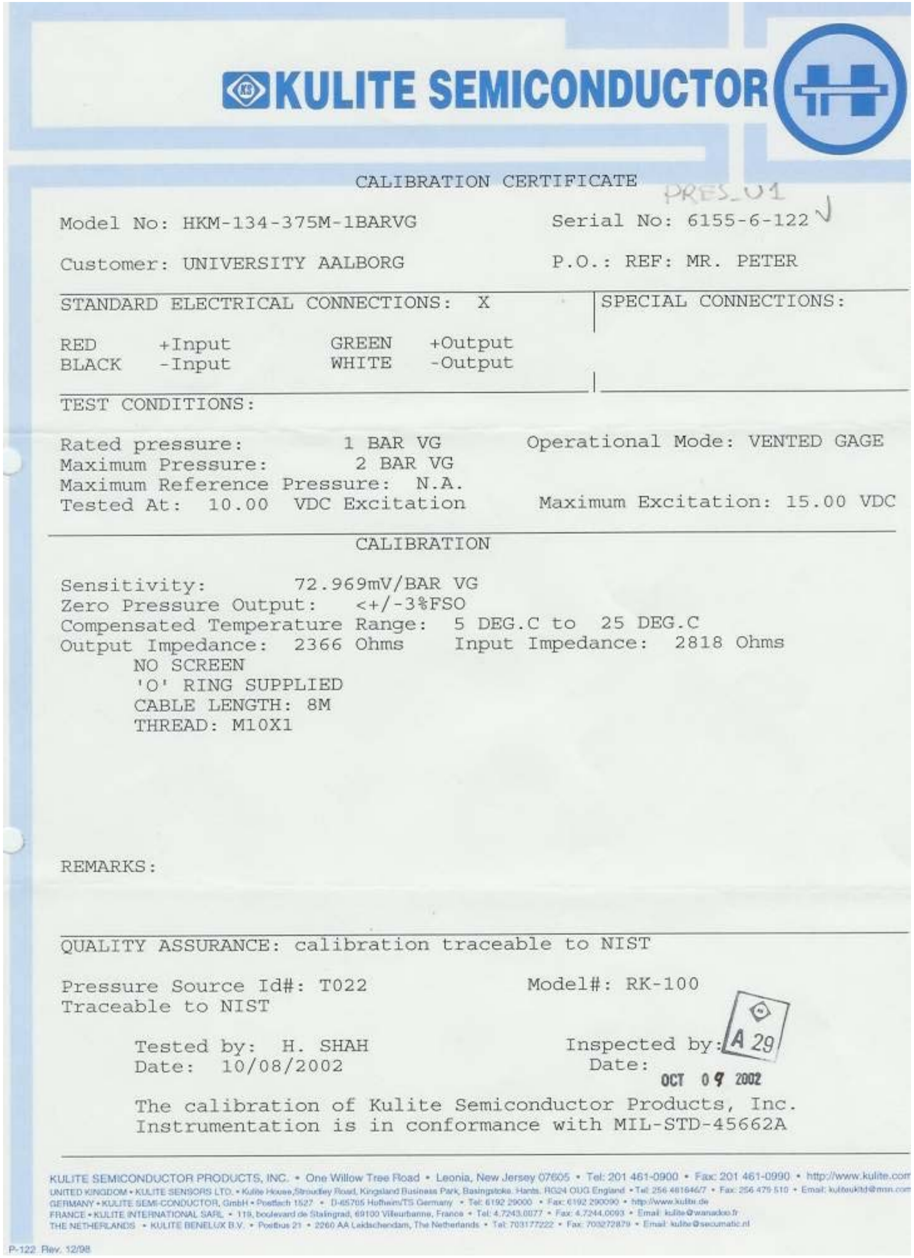
Below all transducers connected to the MGC+ is listed, see Table 2.1. In the following chapters the transducers are called by the tags given in this table. The table also gives the make and model of the individual transducers as well as what board in the MGC+ they are connected to. Also the location of the individual transducers are given in the table.

#	Tag	Sensor description	Range Min	Range Max	Unit	Placement	Spec.	Make	Model	MGC+ front	MGC+ back	MGC+ ch. no.
1	PRES_U1	Pressure cell, for salt water	0	10	m	on centerline, under ramp	DEA	Kulite	HKM-134-375M-1BarVG	ML-801 signal processing module	AP-810 connection board for SG	1.1
2	PRES_U2	Pressure cell, for salt water	0	10	m	on centerline, under center of gravity	DEA	Kulite	HKM-134-375M-1BarVG			1.2
3	PRES_U3	Pressure cell, for salt water	0	10	m	under starboard, aft corner	DEA	Kulite	HKM-134-375M-1BarVG			1.3
4	PRES_U4	Pressure cell, for salt water	0	10	m	under port, aft corner	DEA	Kulite	HKM-134-375M-1BarVG			1.4
5	PRES_R1	Pressure cell, for salt water	0	10	m	in reservoir, in turbine area	DEA	Kulite	HKM-134-375M-1BarVG			1.5
6	PRES_R2	Pressure cell, for salt water	0	10	m	in reservoir, in turbine area	DEA	Kulite	HKM-134-375M-1BarVG			1.6
7	PRES_R3	Pressure cell, for salt water	0	10	m	in reservoir, in turbine area	DEA	Kulite	HKM-134-375M-1BarVG			1.7
8	PRES_P	Pressure cell, for salt water	0	10	m	on mooring pile, 1 - 3 m below MWL	DEA	Kulite	HKM-134-375M-1BarVG			1.8
9	PRES_AC1	Pressure cell, for air tubes	0	10	m	in air chamber, zone 1	DEA	Kulite	HKM-134-375M-1BarVG	ML-801 signal processing module	AP-810 connection board for SG	2.1
10	PRES_AC2	Pressure cell, for air tubes	0	10	m	in air chamber, zone 2	DEA	Kulite	HKM-134-375M-1BarVG			2.2
11	PRES_AC3	Pressure cell, for air tubes	0	10	m	in air chamber, zone 3	DEA	Kulite	HKM-134-375M-1BarVG			2.3
12	PRES_AC4	Pressure cell, for air tubes	0	10	m	in air chamber, zone 4	DEA	Kulite	HKM-134-375M-1BarVG			2.4
13	PRES_AC5	Pressure cell, for air tubes	0	10	m	in air chamber, zone 5	DEA	Kulite	HKM-134-375M-1BarVG			2.5
14	PRES_FL	Pressure cell, for salt water	0	10	m	on centerline, under ramp crest	DEA	Kulite	HKM-134-375M-1BarVG			2.6
		Pressure cell, for air tubes	0	10	m	in air chamber, zone RESERVE	DEA	Kulite	HKM-134-375M-1BarVG			2.7
		Pressure cell, for air tubes	0	10	m	in air chamber, zone RESERVE	DEA	Kulite	HKM-134-375M-1BarVG			2.8
17	FORCE_M	Force transducer	0	100	kN	in main mooring cable at pile	DEA	HBM	U2B-100	ML-801 signal processing module	AP-810 connection board for SG	3.1
18	FORCE_C	Force transducer	0	50	kN	in cross cable at starboard starboard reflector, on verical line close to shoulder	DEA	HBM	U2B-50			3.2
19												3.3
20												3.4
21												3.5
22												3.6
23												3.7
24												3.8
25	ACC_P1	Accelerometer	0	20	m/s^	in control room, horizontal, parallel to centerline.	DEA			ML-801 signal processing module	AP-801 connection board analogue signals	4.1
26	ACC_P2	Accelerometer	0	20	m/s^	in control room, vertical	DEA					4.2
27	ACC_P3	Accelerometer	0	20	m/s^	on starboard shoulder, vertical	DEA					4.3
28	ACC_P4	Accelerometer	0	20	m/s^	on port shoulder, vertical	DEA					4.4
29	ACC_R1	Accelerometer	0	20	m/s^	on port reflector, near pad eye for cross wire, horisontal, perpendicular to reflector	DEA					4.5
30	ACC_R2	Accelerometer	0	20	m/s^	on port reflector, near pad eye for cross wire, vertical	DEA					4.6
31	HEEL	Inclinometer			°		EU	Spectrotilt	SSY0185-VAS			4.7
32	TRIM	Inclinometer			°		EU	Spectrotilt	SSY0185-VAS			4.8
33	DISP_1	Displacement sensor	-0.25	0.25	m	in shoulder connection, in shoulder center line, 0.25 m above deck	EU Dur. eq. item 3 WP 1	ASM	PCQA21/1000	ML-801 signal processing module	AP-801 connection board analogue signals	5.1
34	DISP_2	Displacement sensor	-0.5	0.5	m	in shoulder connection, in shoulder center line, 1.75 m above deck	EU Dur. eq. item 3 WP 1	ASM	PCQA21/500			5.2
35	DISP_3	Displacement sensor				in shoulder connection, ortogonal to shoulder center line, 0.25 m above deck	EU Dur. eq. item 3 WP 1	ASM				5.3
36	DISP_4	Displacement sensor				in shoulder connection, ortogonal to shoulder center line, 1.75 m above deck	EU Dur. eq. item 3 WP 1	ASM				5.4
37	WINDSP	Wind speed sensor	0	?	m/s^	On top of control room	EU Dur. eq. item 5 WP 1.5					5.5
38	WINDDIR	Wind direction sensor	0	360	°	On top of control room	EU Dur. eq. item 5 WP 1.5					5.6
39												5.7
40												5.8
41	SG_SH1	SG rosette 1				SG 1 in rosette 1 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM		ML-801 signal processing module	AP-810 connection board for SG	6.1
42	SG_SH2	SG rosette 2				SG 2 in rosette 1 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				6.2
43	SG_SH3	SG rosette 3				SG 3 in rosette 1 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				6.3
44	SG_SH4	SG rosette 1				SG 1 in rosette 2 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				6.4
45	SG_SH5	SG rosette 2				SG 2 in rosette 2 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				6.5
46	SG_SH6	SG rosette 3				SG 3 in rosette 2 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				6.6
47	SG_SH7	SG rosette 1				SG 1 in rosette 3 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				6.7
48	SG_SH8	SG rosette 2				SG 2 in rosette 3 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				6.8
49	SG_SH9	SG rosette 3				SG 3 in rosette 3 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM		ML-801 signal processing module	AP-810 connection board for SG	7.1
50	SG_SH10	SG rosette 1				SG 1 in rosette 4 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				7.2
51	SG_SH11	SG rosette 2				SG 2 in rosette 4 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				7.3
52	SG_SH12	SG rosette 3				SG 3 in rosette 4 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				7.4
53	SG_SH13	SG rosette 1				SG 1 in rosette 5 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				7.5
54	SG_SH14	SG rosette 2				SG 2 in rosette 5 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				7.6
55	SG_SH15	SG rosette 3				SG 3 in rosette 5 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				7.7
56	SG_SH16	SG rosette 1				SG 1 in rosette 6 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				7.8
57	SG_SH17	SG rosette 2				SG 2 in rosette 6 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM		ML-801 signal processing module	AP-810 connection board for SG	8.1
58	SG_SH18	SG rosette 3				SG 3 in rosette 6 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				8.2
59	SG_SH19	SG rosette 1				SG 1 in rosette 7 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				8.3
60	SG_SH20	SG rosette 2				SG 2 in rosette 7 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				8.4
61	SG_SH21	SG rosette 3				SG 3 in rosette 7 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				8.5
62	SG_SH22	SG rosette 1				SG 1 in rosette 8 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				8.6
63	SG_SH23	SG rosette 2				SG 2 in rosette 8 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				8.7
64	SG_SH24	SG rosette 3				SG 3 in rosette 8 in shoulder, on vertical line on outer plate between J and K, in side	EU Cons. item 3 WP 1.5	HBM				8.8
65	SG_RC1	SG rosette 1				SG 1 in rosette 1 in port reflector, on verical line close to cross wire connection	EU Cons. item 3 WP 1.5	HBM		ML-801 signal processing module	AP-810 connection board for SG	9.1
66	SG_RC2	SG rosette 2				SG 2 in rosette 1 in port reflector, on verical line close to cross wire connection	EU Cons. item 3 WP 1.5	HBM				9.2
67	SG_RC3	SG rosette 3				SG 3 in rosette 1 in port reflector, on verical line close to cross wire connection	EU Cons. item 3 WP 1.5	HBM				9.3
68	SG_RC4	SG rosette 1				SG 1 in rosette 2 in port reflector, on verical line close to cross wire connection	EU Cons. item 3 WP 1.5	HBM				9.4
69	SG_RC5	SG rosette 2				SG 2 in rosette 2 in port reflector, on verical line close to cross wire connection	EU Cons. item 3 WP 1.5	HBM				9.5
70	SG_RC6	SG rosette 3				SG 3 in rosette 2 in port reflector, on verical line close to cross wire connection	EU Cons. item 3 WP 1.5	HBM				9.6
71	SG_RC7	SG rosette 1				SG 1 in rosette 3 in port reflector, on verical line close to cross wire connection	EU Cons. item 3 WP 1.5	HBM				9.7
72	SG_RC8	SG rosette 2				SG 2 in rosette 3 in port reflector, on verical line close to cross wire connection	EU Cons. item 3 WP 1.5	HBM				9.8
73	SG_RC9	SG rosette 3				SG 3 in rosette 3 in port reflector, on verical line close to cross wire connection	EU Cons. item 3 WP 1.5	HBM		ML-801 signal processing module	AP-810 connection board for SG	10.1
74	SG_RC10	SG rosette 1				SG 1 in rosette 4 in port reflector, on verical line close to cross wire connection	EU Cons. item 3 WP 1.5	HBM				10.2
75	SG_RC11	SG rosette 2				SG 2 in rosette 4 in port reflector, on verical line close to cross wire connection	EU Cons. item 3 WP 1.5	HBM				10.3
76	SG_RC12	SG rosette 3				SG 3 in rosette 4 in port reflector, on verical line close to cross wire connection	EU Cons. item 3 WP 1.5	HBM				10.4
77	SG_RS1	SG rosette 1				SG 1 in rosette 1 in port reflector, on verical line close to shoulder	EU Cons. item 3 WP 1.5	HBM				10.5
78	SG_RS2	SG rosette 2				SG 2 in rosette 1 in port reflector, on verical line close to shoulder	EU Cons. item 3 WP 1.5	HBM				10.6
79	SG_RS3	SG rosette 3				SG 3 in rosette 1 in port reflector, on verical line close to shoulder	EU Cons. item 3 WP 1.5	HBM				10.7
80	SG_RS4	SG rosette 1				SG 1 in rosette 2 in port reflector, on verical line close to shoulder	EU Cons. item 3 WP 1.5	HBM				10.8
81	SG_RS5	SG rosette 2				SG 2 in rosette 2 in port reflector, on verical line close to shoulder	EU Cons. item 3 WP 1.5	HBM		ML-801 signal processing module	AP-810 connection board for SG	11.1
82	SG_RS6	SG rosette 3				SG 3 in rosette 2 in port reflector, on verical line close to shoulder	EU Cons. item 3 WP 1.5	HBM				11.2
83	SG_RS7	SG rosette 1				SG 1 in rosette 3 in port reflector, on verical line close to shoulder	EU Cons. item 3 WP 1.5	HBM				11.3
84	SG_RS8	SG rosette 2				SG 2 in rosette 3 in port reflector, on verical line close to shoulder	EU Cons. item 3 WP 1.5	HBM				11.4
85	SG_RS9	SG rosette 3				SG 3 in rosette 3 in port reflector, on verical line close to shoulder	EU Cons. item 3 WP 1.5	HBM				11.5
86	SG_RS10	SG rosette 1				SG 1 in rosette 4 in port reflector, on verical line close to shoulder	EU Cons. item 3 WP 1.5	HBM				11.6
87	SG_RS11	SG rosette 2				SG 2 in rosette 4 in port reflector, on verical line close to shoulder	EU Cons. item 3 WP 1.5	HBM				11.7
88	SG_RS12	SG rosette 3				SG 3 in rosette 4 in port reflector, on verical line close to shoulder	EU Cons. item 3 WP 1.5	HBM				11.8
89	SG_MBC1	SG rosette 1				SG 1 in rosette 1 inside main beam, closest to ramp, on vertical line at CL	EU Cons. item 3 WP 1.5	HBM		ML-801 signal processing module	AP-810 connection board for SG	12.1
90	SG_MBC2	SG rosette 2				SG 2 in rosette 1 inside main beam, closest to ramp, on vertical line at CL	EU Cons. item 3 WP 1.5	HBM				12.2
91	SG_MBC3	SG rosette 3				SG 3 in rosette 1 inside main beam, closest to ramp, on vertical line at CL	EU Cons. item 3 WP 1.5	HBM				12.3
92	SG_MBC4	SG rosette 1				SG 1 in rosette 2 inside main beam, closest to ramp, on vertical line at CL	EU Cons. item 3 WP 1.5	HBM				12.4
93	SG_MBC5	SG rosette 2				SG 2 in rosette 2 inside main beam, closest to ramp, on vertical line at CL	EU Cons. item 3 WP 1.5	HBM				12.5
94	SG_MBC6	SG rosette 3				SG 3 in rosette 2 inside main beam, closest to ramp, on vertical line at CL	EU Cons. item 3 WP 1.5	HBM				12.6
95	SG_MBC7	SG rosette 1				SG 1 in rosette 3 inside main beam, closest to ramp, on vertical line at CL	EU Cons. item 3 WP 1.5	HBM				12.7
96	SG_MBC8	SG rosette 2				SG 2 in rosette 3 inside main beam, closest to ramp, on vertical line at CL	EU Cons. item 3 WP 1.5	HBM				12.8
97	SG_MBC9	SG rosette 3				SG 3 in rosette 3 inside main beam, closest to ramp, on vertical line at CL	EU Cons. item 3 WP 1.5	HBM		ML-801 signal processing module	AP-810 connection board for SG	13.1
98	SG_MBC10	SG rosette 1				SG 1 in rosette 4 inside main beam, closest to ramp, on vertical line at CL	EU Cons. item 3 WP 1.5	HBM				13.2
99	SG_MBC11	SG rosette 2				SG 2 in rosette 4 inside main beam, closest to ramp, on vertical line at CL	EU Cons. item 3 WP 1.5	HBM				13.3
100	SG_MBC12	SG rosette 3				SG 3 in rosette 4 inside main beam, closest to ramp, on vertical line at CL	EU Cons. item 3 WP 1.5	HBM				13.4
101	SG_MBP1	SG rosette 1				SG 1 in rosette 1 inside main beam, on wall parallel with and close to CL, on vertical line	EU Cons. item 3 WP 1.5	HBM				13.5
102	SG_MBP2	SG rosette 2				SG 2 in rosette 1 inside main beam, on wall parallel with and close to CL, on vertical line	EU Cons. item 3 WP 1.5	HBM				13.6
103	SG_MBP3	SG rosette 3				SG 3 in rosette 1 inside main beam, on wall parallel with and close to CL, on vertical line	EU Cons. item 3 WP 1.5	HBM				13.7
104	SG_MBP4	SG rosette 1				SG 1 in rosette 2 inside main beam, on wall parallel with and close to CL, on vertical line	EU Cons. item 3 WP 1.5	HBM				13.8
105	SG_MBP5	SG rosette 2				SG 2 in rosette 2 inside main beam, on wall parallel with and close to CL, on vertical line	EU Cons. item 3 WP 1.5	HBM		ML-801 signal processing module	AP-810 connection board for SG	14.1
106	SG_MBP6	SG rosette 3				SG 3 in rosette 2 inside main beam, on wall parallel with and close to CL, on vertical line	EU Cons. item 3 WP 1.5	HBM				14.2
107	SG_MBP7	SG rosette 1				SG 1 in rosette 3 inside main beam, on wall parallel with and close to CL, on vertical line	EU Cons. item 3 WP 1.5	HBM				14.3
108	SG_MBP8	SG rosette 2				SG 2 in rosette 3 inside main beam, on wall parallel with and close to CL, on vertical line	EU Cons. item 3 WP 1.5	HBM				14.4
109	SG_MBP9	SG rosette 3				SG 3 in rosette 3 inside main beam, on wall parallel with and close to CL, on vertical line	EU Cons. item 3 WP 1.5	HBM				14.5
110	SG_MBP10	SG rosette 1				SG 1 in rosette 4 inside main beam, on wall parallel with and close to CL, on vertical line	EU Cons. item 3 WP 1.5	HBM				14.6
111	SG_MBP11	SG rosette 2				SG 2 in rosette 4 inside main beam, on wall parallel with and close to CL, on vertical line	EU Cons. item 3 WP 1.5	HBM				14.7
112	SG_MBP12	SG rosette 3				SG 3 in rosette 4 inside main beam, on wall parallel with and close to CL, on vertical line	EU Cons. item 3 WP 1.5	HBM				14.8
113	SG_RM1	SG rosette 1				SG 1 in rosette 1 in port reflector, on verical line midway between shoulder and pa eye	EU Cons. item 3 WP 1.5	HBM				
114	SG_RM2	SG rosette 2				SG 2 in rosette 1 in port reflector, on verical line midway between shoulder and pa eye	EU Cons. item 3 WP 1.5	HBM				
115	SG_RM3	SG rosette 3				SG 3 in rosette 1 in port reflector, on verical line midway between shoulder and pa eye	EU Cons. item 3 WP 1.5	HBM				
116	SG_RM4	SG rosette 1				SG 1 in rosette 2 in port reflector, on verical line midway between shoulder and pa eye	EU Cons. item 3 WP 1.5	HBM				
117	SG_RM5	SG rosette 2				SG 2 in rosette 2 in port reflector, on verical line midway between shoulder and pa eye	EU Cons. item 3 WP 1.5	HBM				
118	SG_RM6	SG rosette 3				SG 3 in rosette 2 in port reflector, on verical line midway between shoulder and pa eye	EU Cons. item 3 WP 1.5	HBM				
119	SG_RM7	SG rosette 1				SG 1 in rosette 3 in port reflector, on verical line midway between shoulder and pa eye	EU Cons. item 3 WP 1.5	HBM				
120	SG_RM8	SG rosette 2				SG 2 in rosette 3 in port reflector, on verical line midway between shoulder and pa eye	EU Cons. item 3 WP 1.5	HBM				
121	SG_RM9	SG rosette 3				SG 3 in rosette 3 in port reflector, on verical line midway between shoulder and pa eye	EU Cons. item 3 WP 1.5	HBM				
122	SG_RM10	SG rosette 1				SG 1 in rosette 4 in port reflector, on verical line midway between shoulder and pa eye	EU Cons. item 3 WP 1.5	HBM				
123	SG_RM11	SG rosette 2				SG 2 in rosette 4 in port reflector, on verical line midway between shoulder and pa eye	EU Cons. item 3 WP 1.5	HBM				
124	SG_RM12	SG rosette 3				SG 3 in rosette 4 in port reflector, on verical line midway between shoulder and pa eye	EU Cons. item 3 WP 1.5	HBM				

Table 2.1. List of transducers connected to the MGC+.

3. Pressure transducers

A total 14 pressure transducers are currently deployed at WD-NB. The transducers are calibrated from manufacturer, see Figure 3.1, and the calibration constants have been checked before deployment.



KULITE SEMICONDUCTOR

CALIBRATION CERTIFICATE

PRES_01

Model No: HKM-134-375M-1BARVG Serial No: 6155-6-122

Customer: UNIVERSITY AALBORG P.O.: REF: MR. PETER

STANDARD ELECTRICAL CONNECTIONS: X | SPECIAL CONNECTIONS:

RED +Input GREEN +Output
BLACK -Input WHITE -Output

TEST CONDITIONS:

Rated pressure: 1 BAR VG Operational Mode: VENTED GAGE
Maximum Pressure: 2 BAR VG
Maximum Reference Pressure: N.A.
Tested At: 10.00 VDC Excitation Maximum Excitation: 15.00 VDC

CALIBRATION

Sensitivity: 72.969mV/BAR VG
Zero Pressure Output: <+/-3%FSO
Compensated Temperature Range: 5 DEG.C to 25 DEG.C
Output Impedance: 2366 Ohms Input Impedance: 2818 Ohms
NO SCREEN
'O' RING SUPPLIED
CABLE LENGTH: 8M
THREAD: M10X1

REMARKS:

QUALITY ASSURANCE: calibration traceable to NIST

Pressure Source Id#: T022 Model#: RK-100
Traceable to NIST

Tested by: H. SHAH Inspected by: A 29
Date: 10/08/2002 Date: OCT 09 2002

The calibration of Kulite Semiconductor Products, Inc.
Instrumentation is in conformance with MIL-STD-45662A

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P-122 Rev. 12/98

Figure 3.1 Example of calibration report from manufacturer for pressure transducer.

The calibration constants have been found to be correct. The calibration constants for the individual transducers are quoted in the table below.

#	Tag	MGC+ ch. no.	Serial no.	Calib.	
1	PRES_U1	1.1	6155-6-122	72.969	mV/BAR VG
2	PRES_U2	1.2	6155-6-124	72.380	mV/BAR VG
3	PRES_U3	1.3	6155-6-125	72.760	mV/BAR VG
4	PRES_U4	1.4	6155-6-126	74.470	mV/BAR VG
5	PRES_R1	1.5	6155-6-127	71.530	mV/BAR VG
6	PRES_R2	1.6	6155-6-128	72.489	mV/BAR VG
7	PRES_R3	1.7	6155-6-129	74.340	mV/BAR VG
8	PRES_P	1.8	6155-6-132	73.170	mV/BAR VG
9	PRES_AC1	2.1	6155-6-133	72.360	mV/BAR VG
10	PRES_AC2	2.2	6155-6-134	74.119	mV/BAR VG
11	PRES_AC3	2.3	6155-6-135	73.150	mV/BAR VG
12	PRES_AC4	2.4	6155-6-136	72.599	mV/BAR VG
13	PRES_AC5	2.5	6155-6-137	74.569	mV/BAR VG
14	PRES_FL	2.6	6155-6-117	75.070	mV/BAR VG
		2.7			
		2.8			

Table 3.1. Calibration constants for pressure transducers.

Some drift in the offset for the individual transducers has been observed – especially for the transducers PRES_U1-4 (placed underneath the structure) used for measuring the floating level, heel and trim of the reservoir part of the device. This is most probably due to marine growth on the transducers. Subsequently, an extra retractable pressure transducer (PRES_FL) and the two inclinometers have been installed. Thus, PRES_U1-4 are no longer needed and currently only used for reference.

The operation of the pressure transducer at the pile PRES_P, used for measuring the wave conditions, has been influenced by the fact that the signal cable to the pile has been damaged on more than one occasion. Currently the cable has been temporarily fixed, but a replacement of the current cable is highly needed in order to insure continuous measurements from PRES_P.

4. Force transducers

A total of two force transducers have been deployed at WD-NB. The transducers have been calibrated by the manufacturer, and the calibration has been verified prior to installation. The calibration constants for the individual transducers are quoted in the table below.

#	Tag	MGC+ ch. no.	Serial no.	Calib.	
17	FORCE_M	3.1	J57384	-1.9996	mV/V
18	FORCE_C	3.2	J74671	-2.0005	mV/V
19		3.3			
20		3.4			
21		3.5			
22		3.6			
23		3.7			
24		3.8			

Table 4.1. Calibration constants for force transducers.

The performance of FORCE_M measuring the mooring forces in the main mooring line attaching WD-NB to the pile, has been influenced by the fact that the signal cable to the pile has been damaged on more than one occasion. Currently the cable has been temporarily fixed, but a replacement of the current cable is highly needed in order to insure continuous measurements from FORCE_M.

The force transducer meant for measuring the forces in the cross mooring line between the reflectors FORCE_C was damaged during the first reflector accidents (described in Kofoed & O'Donovan, 2003). Especially the cable to the transducer was damaged. The transducer has been brought to the workshop for repair and is currently back in place. However, the reflector accidents experienced have also damaged the signal cables going to the port reflector, and the correct functioning of FORCE_C is currently awaiting the re-establishing of these cables.

5. Accelerometers

A total of six accelerometers are to be deployed at WD-NB. The two of these meant for placement on the port reflector has not yet been put in place, due to the accidents experienced with the reflectors. This awaits the re-installation of the signal cables to the port reflector. The two accelerometers placed on the starboard and port shoulder on the platform was initially installed and tested before deployment of WD at test site 1. However, due to damage done to the signal cabling to the shoulder they have not yet been in action. The two accelerometers placed in the equipment container have been delivering data continuously since deployment of WD at test site 1.

All accelerometers are rented from The Structural Research Laboratory, Aalborg University, who also provided the amplifier box and calibration constants for the instruments, see Figure 5.1.

Certifiicate of Calibration
Acceleration/Inclinometer

Lucas Control Systems
543 Ipswich Road
Slough Berkshire SL1 4EC
England

Certificate Number: 92/1136

1V ~ 0,981 m/sec²

ACC_P3

TYPE A223-0001	RANGE +/- 0.5 g	SERIAL NUMBER	11244
Calibration record at 25°C			
Excitation / supply	+/-15 Volts	Output impedance	10.063 k Ohms
Excitation supply current	+/-5 mA		

Maximum Voltage	5.003 V	Zero offset	0.004 V
Minimum Voltage	-4.996 V	Natural Frequency	62 HZ
Full Scale Output	9.999 V	Damping Ratio	0.63
Cross Axis Sens.	0.001 g/g	Noise	<0.003 V / Rms
Non Linearity	0.012 %FRO	Hysterisis	0.010 % FRO

Input	Output	LSF Calced.	% FSO Dev.
-0.500	-4.996	-4.996	-0.004
-0.400	-3.997	-3.996	0.008
-0.300	-2.996	-2.996	-0.001
-0.200	-1.996	-1.996	0.001
-0.100	-0.997	-0.996	0.012
0.000	0.004	0.004	0.004
0.100	1.006	1.005	-0.015
0.200	2.007	2.005	-0.023
0.300	3.004	3.005	0.008
0.400	4.006	4.005	-0.011
0.500	5.003	5.005	0.021

Calc. Zero Error	0.0044 Volts
Sensitivity	10.0015 Volts per g
Maximum Error	0.0023 Volts
STD Error Non Linearity	0.0121 %FRO

TEMP	OFFSET	Test Output Volts
-54	-0.004	0.000
22	0.004	0.000
95	0.008	0.000
Bias Temp coefficient		0.0008 % Full Scale / deg. C
Scale Factor Temperature Coefficient		0.0000 % Reading / deg. C

Change of o/p with Supply	N/A	Capsule No.	N/A
Switching Regulator Spike	N/A		
Bonding Connector	N/A		
Stiction	1mV		
Friction	1 mV		
Insulation	> 20 Mohms @ 100VOLTS DC		

QUALITY CONTROL
Signature ______ Date 14/04/2000
Test number SSA-220

9FRM-037X ISSUE5

Lucas VARITY

Figure 5.1 Example of calibration report for accelerometer.

The functioning of the instruments and the calibration were checked prior to installation on board WD-NB, see Figure 5.2.

#	Tag	MGC+ ch. no.	Serial no.	Calib.	
25	ACC_P1	4.1	11246	1.961	(m/s^2)/V
26	ACC_P2	4.2	11243	0.981	(m/s^2)/V
27	ACC_P3	4.3	11244	0.981	(m/s^2)/V
28	ACC_P4	4.4	11360	0.981	(m/s^2)/V
29	ACC_R1	4.5	11361	1.963	(m/s^2)/V
30	ACC_R2	4.6	11362	1.962	(m/s^2)/V

Table 5.1. Calibration constants for accelerometers.

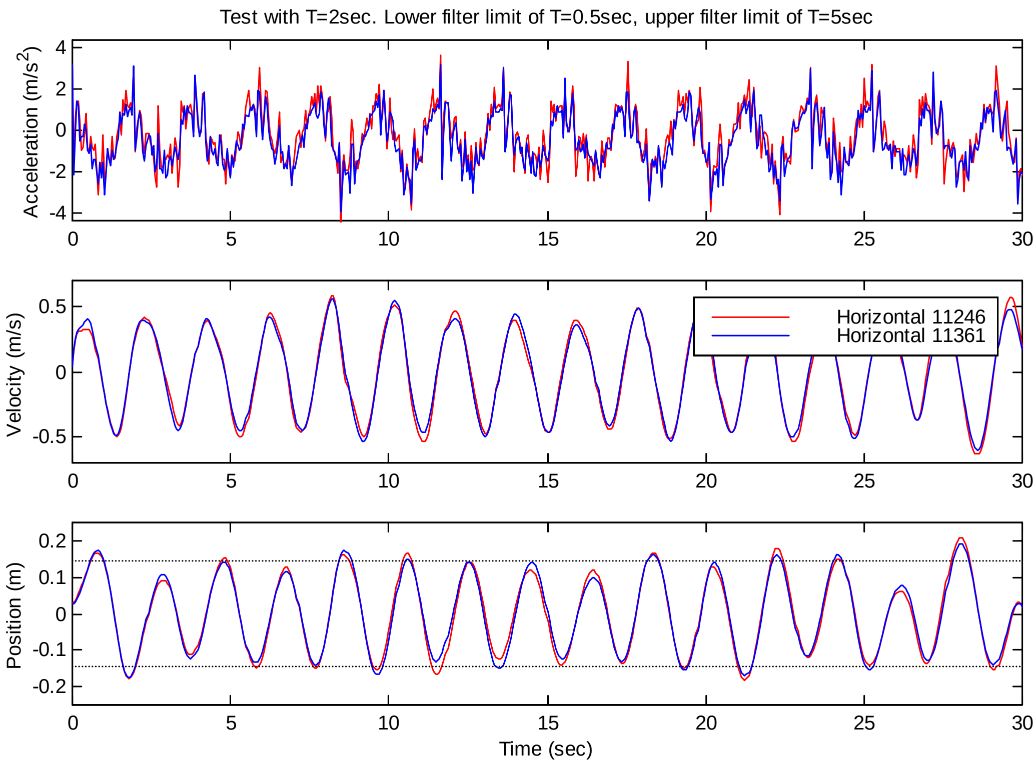

Figure 5.2. Example of check of the calibration and functioning of the accelerometers (applied amplitude of oscillation was 0.146 m, indicated with the horizontal line in the lowest graph).

6. Displacement sensors

The displacement sensors meant for measuring the relative movements in the port shoulder junction have not yet been installed. This is due to the accidents experienced with the reflectors.

The sensors are calibrated by manufacturer and will be checked once installed.

7. Strain gauges

All 84 strain gauges, mounted as rosettes of three, were installed prior to the deployment of WD. All rosettes were of the same type and with the same characteristics which has been given by the manufacturer HBM, see scan hereof in Figure 7.1.

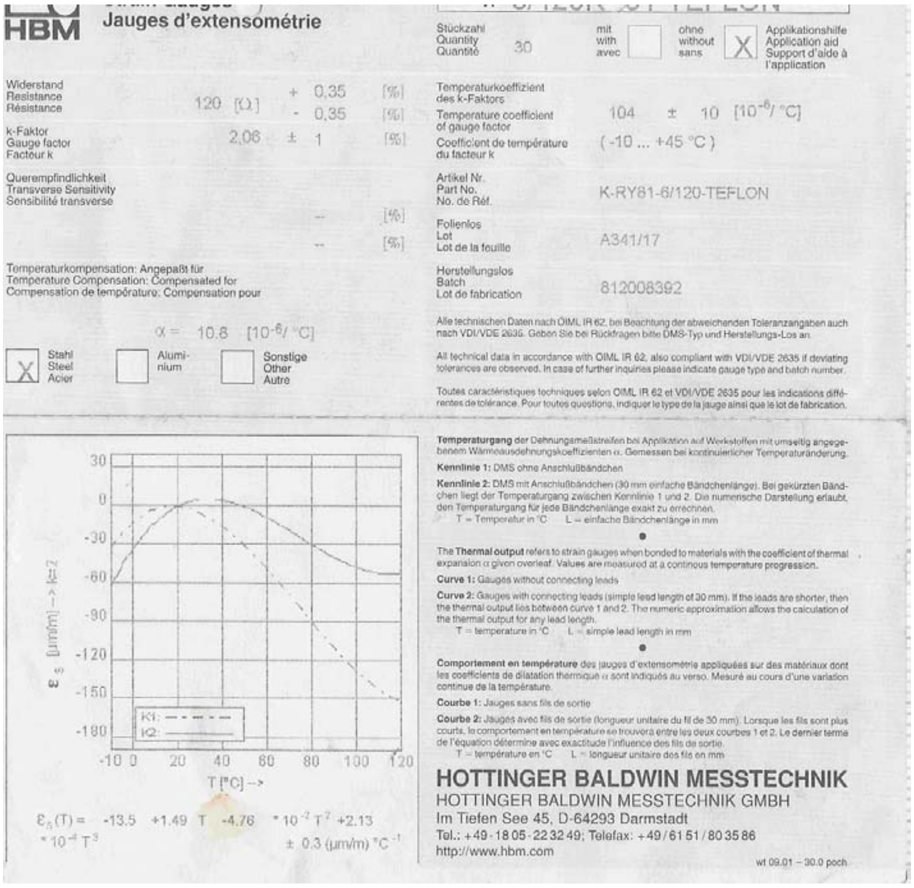

Figure 7.1. Characteristics of rosette strain gauges used on board WD-NB.

All rosettes were tested after application. However, due to the reflector accidents and the following problems with signal cable to port reflector and shoulder, the strain gauges in this part of the structure has not been tested or utilized so far. The strain gauges placed in the central part of the platform seems to working, but due to time constraints no detailed measurements with these have been conducted so far.

8. Inclinometers

Due to problems with the pressure transducers placed underneath the platform, two inclinometers have been installed in order to obtain direct measurements of heel and trim of the platform. The inclinometers have a calibration constant of 60 mV/°.

The inclinometers are giving more reliable readings of the heel and trim than was obtained using the pressure transducers. However, some minor changes in the offset of especially the trim readings occasionally occur. The reason for this is yet to be found.

9. Siphon turbine

A preliminary calibration of the siphon turbine was carried out by Kofoed & O´Donovan, 2003 as given below.

Turbine calibration data (screen-dump from SCADA system, see Figure 9.1) comprising time plots of Turbine Rotational Speed (N), Turbine Power (P), Relative Basin Level (RBL) and Floating Level (FL) have been established for various values of Basin Work Span (BWS).

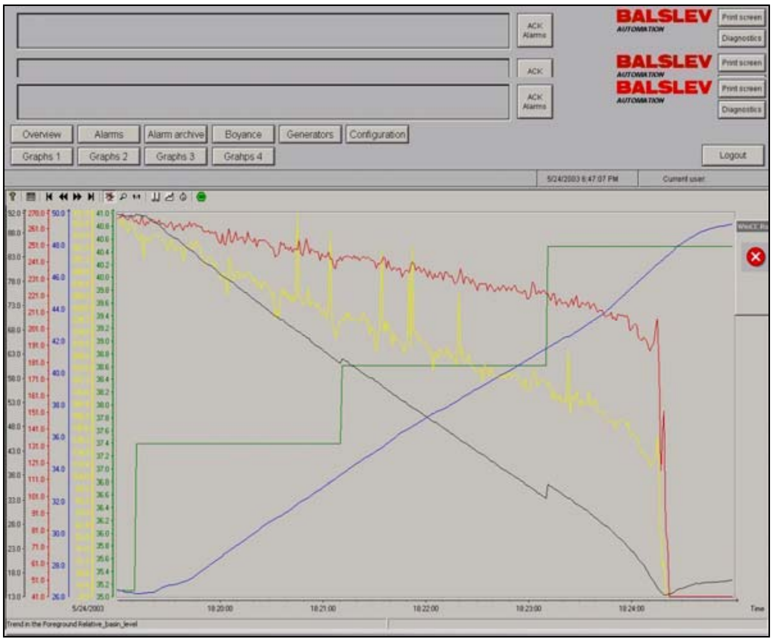

Figure 9.1. Turbine calibration plot

This plot was used to estimate the specific speed for the siphon turbine in use on WD by carrying out the following steps:

- Divide the plots into 20 second intervals, noting the values for N, P, RBL & FL at each interval.
- Calculate the Reservoir Area from the accompanying CAD drawing.
- Calculate the Basin Level (BL) = Crest Height – ((1-RBL)xBWS)
- Calculate Flowrate (Q) = (Reservoir Area x Change in BL)/Time Interval
- Calculate Head (H) = Average Floating Level – [(1-Average RBL)x BWS]
- Specific speed, NS = $\frac{N\sqrt{Q}}{H^{0.75}}$
- Crest Height = Vertical Distance from floor (turbine level) to the crest.

From such data a specific speed of 340.6 resulted.
Primarily due to corrosion of a vital part of the shaft, the oil lubricated bearing in the siphon turbine has been damaged. This entails that the turbine has been taken out of service.

10. Dummy turbines

In order to use the dummy turbines for measuring the discharge, these have been calibrated by filling up the reservoir and emptying it while measuring the falling water level in the reservoir and the position of the reservoir. The performed calibrations are described below.

10.1 Introduction

The aim of the measurements was to determine a function for the discharge of the dummy turbines depending on the head between basin level and sea level. Significant differences in the behaviour of the three valves should also be identified. These differences can arise from the asymmetric arrangement of the valves, which causes unequal flow conditions. The measurements should furthermore detect any interaction between the dummy turbines.

The arrangement of the dummy valves and the pressure transducers is the following:

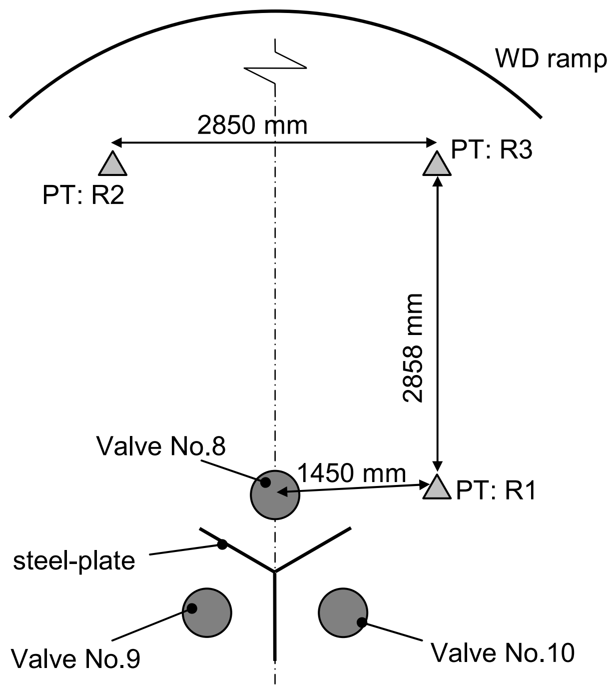

Figure 10.1. Arrangement of valves and pressure transducers.

The pressure transducers R1, R2, R3 are used to determine the water level in the basin, they are mounted 35 mm above deck level.

There are three steel plates situated between the dummy valves, each of them with a height of 300 mm above deck level. Their purpose is to guide the flow to the valves and to prevent interaction between the valves. As the work span of the water level in the basin is between 300 mm and 600 mm above deck level, the water level should never be lower than the upper edge of the steel plates.

10.2 Measuring and data interpretation

The measurements were all made at the same crest height of the Wave Dragon, which means that the air mass in the chambers below the Wave Dragon was never changed. A variation of the crest height was not possible due to the weather conditions and the necessary time span for the compensation of the movements after changing the level.

Before each measurement the basin was filled completely by pumping water into it. After the water surface had calmed down, the dummy turbines were opened manually from the SCADA control system and closed after the surface had reached the minimum basin level $h_{bas,min} = 300\ mm$. The raw data of seven pressure transducers (three for the basin level on deck: R1, R2, R3; four for the vertical position of the Wave Dragon on the bottom of the device: U1, U2, U3, U4) including a time stamp were recorded. The possibility to transfer the calibrated data directly out of the SCADA system was not yet implemented.

For the data interpretation the raw data taken on the Wave Dragon first had to be calibrated. There was no secure information how to use the given calibration constants. The results could only be validated by comparison with screen shots from the SCADA system. During the measuring there were small waves which influenced the quality of the measuring data.

Due to the influence of the waves and the uncertainty concerning the calibration constants, the data interpretation and the results have to be considered as preliminary.

10.3 Results

Discharge, calculated from the basin level

Figure 10.2 to Figure 10.4 show the discharge calculated from the basin level h_{bas} (measured by R1, R2, R3). The discharge is obtained by comparing the water volume in the basin with the time scale. The corresponding head is calculated from the basin level in combination with the Wave Dragon's crest height (measured by U1, U2, U3, U4).

The dashed curve is a manual fit calculated from

$$Q = kA\sqrt{2gH} \,,$$

where $A = \pi/4 * D^2 = 0.147\ m^2$ is the dummy turbine cross section.

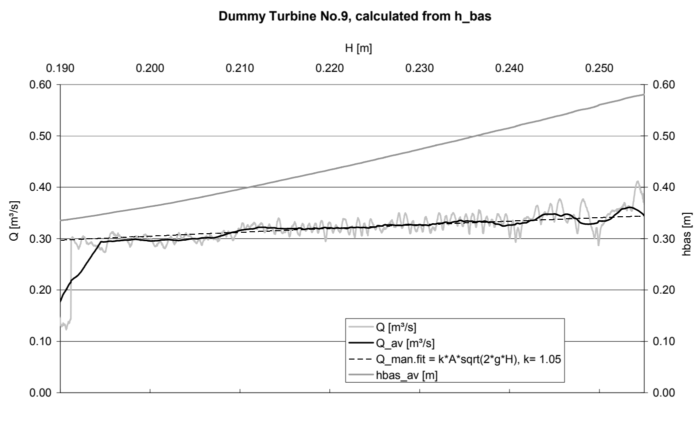

Figure 10.2. Discharge of dummy turbine No. 8.

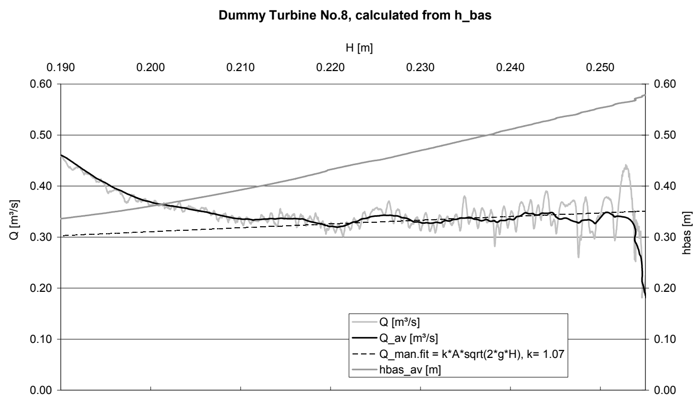

Figure 10.3. Discharge of dummy turbine No. 9.

Especially the discharge curve of dummy turbine No. 8 shows a big discrepancy to the manual fit for $h_{bas} < 0.40\ m$, the discharge seems to increase with lower heads. Furthermore, there is noise in the curves although the discharge Q is averaged twice (see section below). The following chapter gives an explanation for these phenomena.

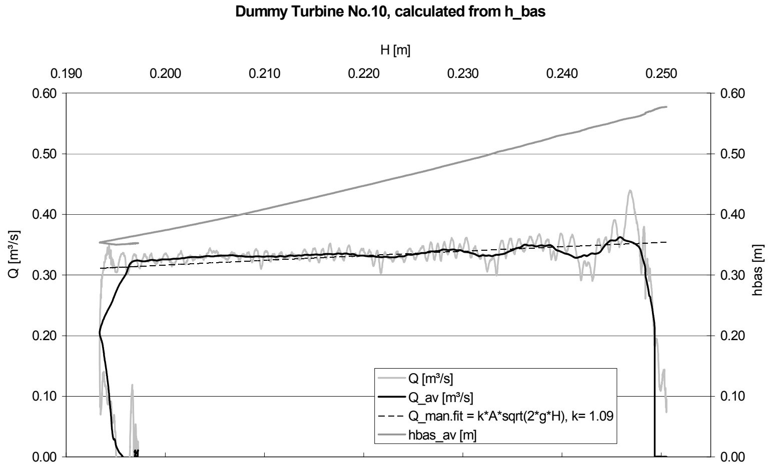

Figure 10.4. Discharge of dummy turbine No.10.

Row 1 in Table 10.1 displays the values of k which have been determined by measuring the discharge in different valve opening situations. The second row shows the average value of k calculated from the single values in columns 8, 9 and 10. The discrepancies between row 2 and row 3 are smaller than 2.7 %, there seems to be no significant interaction between the valves.

Valve No.	8	9	10	8+9	8+10	9+10	8+9+10
k	1.07	1.05	1.09	1.08	1.09	1.07	1.10
k_av	-	-	-	1.06	1.08	1.07	1.07
$\|(k-k\_av)/k\|$	-	-	-	1.9%	0.9%	0.0%	2.7%

Table 10.1. Values of *k*, determined from the calculations of the basin level.

Reasons for the discharge discrepancies

a) Waves in the basin

The values needed to calculate the discharge curves in Figure 10.2 to Figure 10.4, namely h_{bas} and H, are averaged over ten seconds, the discharge Q itself is then again averaged over ten seconds, but the discharge curve $Q(H)$ is still unsteady. The combination of the water surface movements in the basin and the sea waves is responsible for the quality of the discharge curves.

b) Non-planar water surface

During the discharge the water surface in the basin is not strictly planar. Especially at lower basin levels a depression in the middle of the basin was observed. The pressure transducers R1, R2, R3 used to calculate the basin level and the discharge in Figure 10.2 to Figure 10.4 are situated in this depression. Thus, the measured level decreases faster than the real average level, hence the calculated discharge is larger than the real one.

According to Figure 10.2 to Figure 10.4 it is possible to specify minimum basin levels above which the water surface seems to be planar:

Valve No.	8	9	10	8+9	8+10	9+10	8+9+10
$h_{bas}\ [m]$	>0.40	>0.35	>0.35	>0.40	>0.45	>0.35	>0.47

Table 10.2. Minimum basin levels with planar water surface.

The following figure shows the influence of the non-planar surface for different valve combinations:

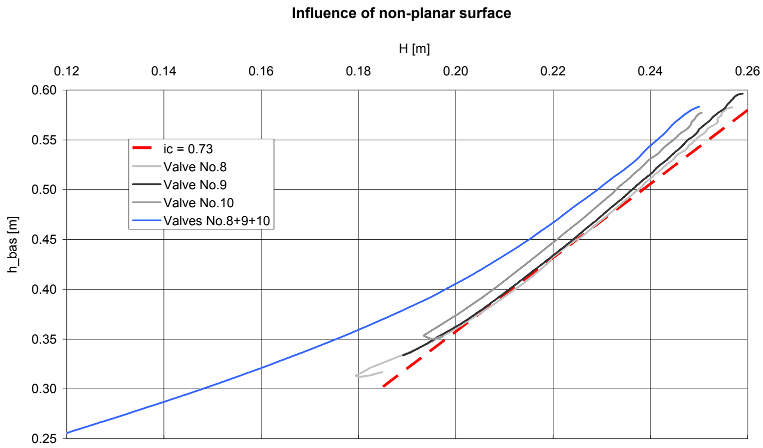

Figure 10.5. Influence of non-planar surface.

The more valves are opened, the larger is the discrepancy between measured and real average head H. The closing point of the valves can be identified in the curves of valve No. 8 and valve No. 10: The water level is levelling out, the curves meet again the "normal" immersion curve which is defined by an immersion coefficient of "$ic = 0.73$".

The reasons for the formation of a non-planar water surface in the basin are:

- The swash plates, which are placed on the Wave Dragon in order to keep ballast water on deck are restricting the water from flowing towards the middle of the basin.
- The dynamic pressure, which increases significantly in the region of the dummy turbines is lowering the static pressure height especially at lower basin levels.

Figure 10.6 shows the dimension of p_{dyn} with valve No. 8 opened, calculated at the position of the valve nearest pressure transducer R1. The dynamic pressure depending on the basin level is obtained by calculating the following quantities:

- the head H from h_{bas} with the immersion coefficient ic and a starting point $h_{bas} = 0.60\ m$, $Rc0 = 0.25\ m$ resp. $0.90\ m$
- the discharge $Q(h_{bas})$ from $Q = k \cdot A\sqrt{2gH(h_{bas})} = 1.05 \cdot 0.147 m^2 \sqrt{2gH(h_{bas})}$
- the flow area, using half of a cylinder with a radius of $r = 1.45\ m$ around valve No. 8 touching the pressure transducer R1
- the average flow velocity c and with it the dynamic pressure $p_{dyn} = \rho/2 \cdot c^2$

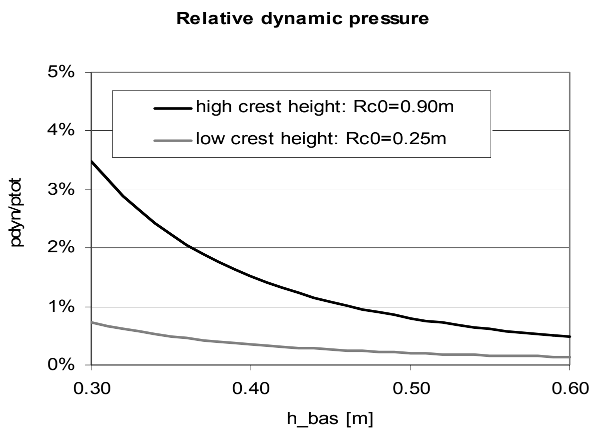

Figure 10.6. Influence of dynamic pressure.

At lower crest heights the dynamic pressure can be neglected. However, it should be noted that at a crest height of $Rc0 = 0.90\ m$ the proportion of the dynamic pressure can rise to 3.5% of the total pressure, thus leading to a further depression of the surface near the pressure transducers.

Discharge, calculated from Wave Dragon crest height

Another possibility to calculate the discharge is to determine the water volume in the basin from the crest height, taking the immersion coefficient into account. The advantage of this method is that the total mass of the water in the reservoir is determined by measuring the immersion, thus avoiding the aforementioned problems in measuring the reservoir level. Starting with a filled basin (h_{bas} = 0.60 m) at a certain crest height $Rc0$, the basin level can be evaluated from

$$\Delta h_{bas} = -\frac{\Delta Rc}{ic},$$

where ic is the immersion coefficient. The crest height is measured using the pressure transducers U1, U2, U3, U4.

Due to the irregular structure of the hull, the immersion coefficient ic is a complex function of the crest height and the volume of the compressible air enclosed in the ballast tanks. This function has not yet been determined. As a simplifying assumption a constant immersion coefficient ic = 0.73 has been used. The discharge characteristic thus derived is shown in Figure 10.7.

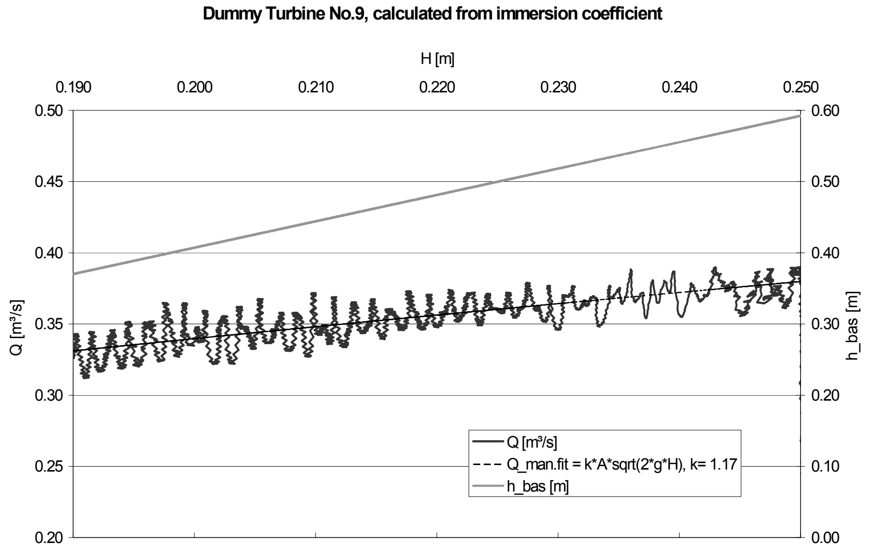

Figure 10.7. Discharge of dummy turbine No. 9.

The calculated curve contains oscillations resulting from sea waves, but it can be fitted with the function $Q = kA\sqrt{2gH}$ quite well (see the curve "Q_man.fit" in the figure).

Table 10.3 refers to the above calculations from the immersion coefficient and corresponds to Table 10.1. The values of k are larger than those given in Table 10.1. A possible reason is the use of a constant immersion coefficient, which is not a perfectly realistic assumption.

Valve No.	8	9	10	8+9	8+10	9+10	8+9+10
A [m^2]	0.147	0.147	0.147	0.294	0.294	0.294	0.441
k	1.17	1.17	1.20	1.20	1.20	1.20	1.17

Table 10.3. Values of *k*, determined from the measured crest height.

10.4 Conclusions

Given the difficulty of determining the exact function ic (Rc, h_{bas}), it seems advisable to use the pressure transducers R1, R2, R3 in the basin for the calculation of the discharge rather than using the crest height. The results of the calculations are listed below: Row 2 shows the values of k, row 3 compares these values with the siphon turbine model test results in the laboratory, taking the different cross-sectional areas into account. It can be concluded that the discharge of each dummy turbine is approx. 2.3 times the one of the siphon turbine.

	Siphon Turbine	Valve No. 8	Valve No. 9	Valve No. 10	Valves No. 8+9	Valves No. 8+10	Valves No. 9+10	Valves No. 8+9+10
A [m^2]	0.0908	0.147	0.147	0.147	0.294	0.294	0.294	0.441
k [-]	0.754	1.07	1.05	1.09	1.08	1.09	1.07	1.10
$A \cdot k \,/\, A \cdot k_{Siptur}$ [-]	1.00	2.30	2.25	2.34	4.64	4.68	4.59	7.09

Table 10.4. Test results and comparison with the siphon turbine.

The results of the measurements have to be considered as preliminary due to the following reasons:

- no data acquisition possible for siphon turbine.
- only raw data of dummy turbine measurements available, no secure information about how to calibrate the data.
- no ideal weather conditions.

For further measurements the following requirements have to be fulfilled:

- complete functioning data acquisition for siphon turbine (quantities Rc, h_{bas}, n_{tur}, P_{tur}).
- secure information about the calibration of the raw data from the pressure transducers.
- calm sea, no overtopping at $Rc0 = 0.2\ m$.
- known correlation between the immersion coefficient and $Rc0$ at a certain air chamber setting.

11. Literature

Kofoed, J. P. and O'Donovan, E., 2003: *Status report – First offshore experiences,Wave Dragon, Nissum Bredning*. The Hydraulics and Engineering Group, Aalborg University, Nov. 2003.

Kofoed, J. P. and Frigaard, P., 2004: *Automatic control of freeboard and turbine operation – Wave Dragon, Nissum Bredning*. Hydraulics and Engineering No. 1, Dep. of Civil Eng., Aalborg University, February 2004.

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